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Preliminary experience of optical elements fabrication by X-ray lithography

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Abstract

X-ray lithography using synchrotron radiation from the VEPP-3 storage ring was applied for the fabrication of test specimens of some optical elements such as Fresnel lenses and arrays of optical elements for visible light.

A promising advantage of the application of X-ray lithography is the possibility of micron scale patterning on curved surfaces. The patterns of Fresnel-like structures were generated by an annular laser photoplotter for the fabrication of an X-ray mask on a 2-μm-thick silicon membrane with a 1.5-μm-thick gold absorber. The X-ray lithography station at the VEPP-3 storage ring was used for deep X-ray lithography.

1. Introduction

Diffraction lenses for visible light are devices that are mass-produced for a number of important applications. Bifocal interocular lenses and "light needles" for laser players are typical examples of such applications [1,2]. Diffraction microlens matrices are involved in designing the optical interconnections and data buses [3]. Lately the first successful experiments on calculations and synthesis of "deep" (more than 10 wavelengths) diffraction lenses, that will allow one to solve the problem of diffraction components achromatization and to create achromatic single element objectives for the visible spectral range, have obtained peculiar significance [4,5].

An attempt to fabricate diffraction lenses in three steps has been done in the proposed work. At the first step the lens masks were synthesized by direct pattern recording with the use of a narrow laser beam (0.8 μm) on a precise laser photoplotter [6]. At the second step the X-ray masks of the lens were fabricated by replicating the primary mask pattern. The last step, microlens fabrication in polymethylmethacrylate (PMMA), was carried out using synchrotron radiation (at a wavelength of 0.3–1 nm). It allows one to avoid contact between the mask and the PMMA, to replicate the mask pattern on a spherical surface, which is essential for obtaining non-aberration lenses and, finally, to obtain a phase microrelief of the optical element immediately in the material without subsequent chemical treatment.

2. Mask fabrication

The technology for obtaining a primary mask on a laser photoplotter is based on the effect of thermochemical changes taking place in thin metal films under exposure by intensive laser radiation. 100–200 nm thick chromium films were chosen as registration material. Due to the thermal effect of laser radiation to the chromium film a surface oxide layer is formed, for which the etching rate in selective etchants is many times less than that for chromium. This allows one to realize a negative recording [7].

The optimal power is 10–30 mW for the technique of thermochemical recording on chromium films at a recording spot velocity of up to 250 cm/s. This corresponds to an intensity of $(1-3)\times 10^6$ W/cm^2. In this case the maximal spatial frequency for the recorded structures is 1200 lines/mm.

The X-ray masks were prepared with the use of a conventional photolithography technique to replicate the primary mask pattern into the 1.6-μm-thick resist covering the p-type silicon wafer with a 2-μm-thick n^+ doped layer on the planar side. Then, a 1.5-μm-thick gold absorber was electroplated, and a silicon membrane was formed after removing the resistive mask. To form the silicon membrane, the backside etching of the wafer was carried out under a reverse bias of the p–n junction. When the

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etching reached the n^+ layer, an anode oxide was grown and etching stopped. Thus, a silicon membrane was formed.

The structure for the X-ray mask pattern was simulated for an aspheric surface. It was chosen and calculated from considerations that a diffraction lens must be used in tandem with a refraction lens. Such a pair (a flat-convex lens in combination with a kinoform) forms a bifocal system which is applicable for use as an interocular lens allowing us to avoid correction by glasses after its implantation.

The characteristic equation for a diffraction aspheric surface is:

$$V=\alpha_1\rho^2+\alpha_2\rho^4,$$

where α_1 and α_2 are constants, ρ is the radial coordinate and V is the wave aberration. In our case $\alpha_1=-0.003085$ mm^{-1}, $\alpha_2=0.000122$ mm^{-3} and ρ changes in the 0–2.5 mm range. The total diameter of the diffraction pattern is 5 mm, the diameter of the first zone is 650 μm and the width of the last zone is 50 μm.

3. Experiments

To estimate the applicability of different materials for lens fabrication, in our preliminary experiments we made replications through a nickel mesh (30 μm period and 6 μm wire thickness) on various types of glasses and polymers. The VEPP-3 storage ring was used as a source of synchrotron radiation in the wavelength range of 0.3–1 nm [8]. The doses of irradiation were varied from 10 to 100 J/cm^2.

It was possible to obtain for glasses after the treatment (etching) a geometrical relief with a depth of up to 0.3 μm. This value is not enough for the creation of a microlens with the necessary diffraction efficiency.

More promising results were obtained with polymers. A typical example of a mesh replication to a PMMA based polymer ($n_D=1.491$) without any etching is shown in Fig. 1. This scanning electron microscope photograph of a sample cross section allows us to estimate the profile depth. It is about 15 μm after an irradiation dose of 50 J/cm^2. That is enough for obtaining the "deep" diffraction (kinoform) structures suitable for work in the visible spectral range.

The microlens pattern of the X-ray mask was replicated without etching to biology compatible PMMA, which is used for the fabrication of artificial interocular lenses. The response of the material (profile depth versus X-ray irradiation dose) is shown in Fig. 2. As can be seen, the profile depth grows linearly with the dose increasing up to 50 J/cm^2, and material destruction does not occur. For doses higher than 50 J/cm^2, the material destruction occurs and the structure depth reaches to about 3 μm. The region of the linear response is large enough for the creation of microlenses suitable for the formation of the bifocal artificial interocular lens. The profile depth can be increased up to 30 μm under additional treatment (etching), i.e. to obtain the "deep" gratings.

A number of lens structures were fabricated in the standard technical PMMA. The doses of the X-ray irradiation were varied in the range from 10 to 50 J/cm^2. Testing of the lens profile was carried out by a microinterferometer. The response of the material is shown in Fig. 3. An

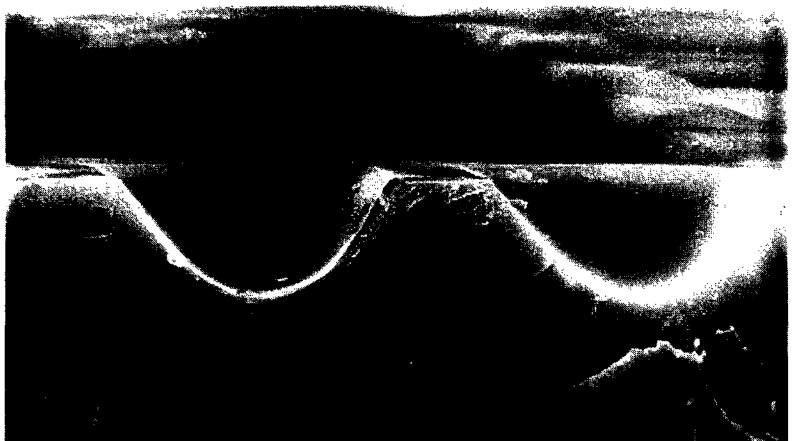

Fig. 1. The cross section of the PMMA-based polymer sample exposed to X-rays through the nickel mesh (30 μm period and 6 μm wires). The photograph is obtained by a scanning electron microscope. The profile depth is about 15 μm after an irradiation dose of 50 J/cm^2.

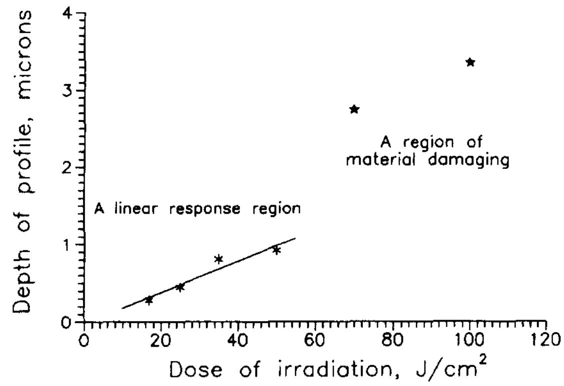

Fig. 2. Response of the PMMA-based material ($n_D = 1.491$) to X-rays (profile depth versus X-ray irradiation dose).

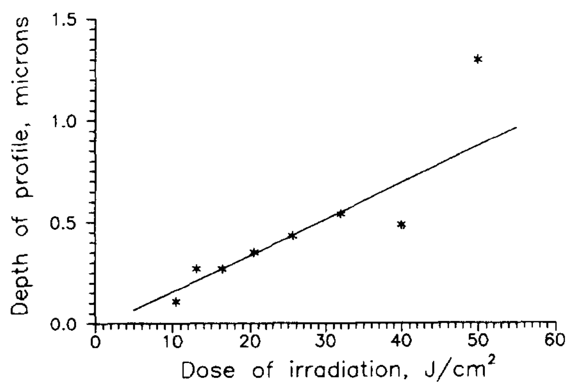

Fig. 3. Dependence of the diffraction microlens profile depth on the X-ray irradiation dose. Lenses were replicated to standard technical PMMA without etching.

acceptable lens profile depth was at a dose of about 30 J/cm^2 of X-ray irradiation. The depth of the relief in this case corresponds to one wavelength of visible light.

4. Conclusions

The performed preliminary experiments demonstrate that it is possible to form an optical polymer microlens by X-ray exposure without chemical treatment. The obtained profile depth of about 1 μm is enough for the fabrication of diffraction kinoform microlenses.

The formation of diffraction kinoform structures on a spherical surface as well as the investigation of the optical properties of the fabricated microlens are subjects for further work.

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